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The Impact of Military Operations on the Spatial Heterogeneity of the Content of Mobile Zinc Compound in Soils of the Sumy Region

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SUMMARY

The purpose of the study is to determine the impact of hostilities on the level of contamination of agricultural lands in the Sumy region with mobile zinc compounds. The object of research was 155 soil samples taken from 6 land plots with a total area of 691.2835 hectares, which were affected by hostilities in the territory of Romensky, Sumy and Okhtyrsky districts of Sumy region. The studied fields were under the influence of intensive hostilities: they were subjected to artillery and mortar shelling; craters, traces of fires and remnants of weapons and ammunition were recorded on them. The study was conducted two years after the resumption of active economic use of the lands, which made it possible to assess the current state of soil contamination under the conditions of their cultivation and partial restoration of agroecosystems. The conducted studies have shown that the content of mobile zinc compounds in agricultural soils of Sumy region is characterized by pronounced spatial heterogeneity, caused by anthropogenic factors, in particular the consequences of hostilities. The largest foci of contamination are located in areas number 1 and number 4. This confirms the local nature of the technogenic impact associated with hostilities. The indicated areas were subjected to mortar and artillery shelling, contained craters, and ammunition residues. Site number 2 and number 5 were characterized by a weak level of contamination, sites number 3 and number 6 were characterized by low and medium levels of contamination. The results obtained justify the need for detailed contamination mapping and the implementation of differentiated approaches to soil quality management to ensure their environmentally safe use in agricultural production.

Keywords: Agricultural Lands; Toxicological Condition; Military Impact; Heavy Metal; Maximum Permissible Concentration; Agrochemical Assessment.

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Introduction

Recent research has increasingly focused on the behavior of zinc in soils exposed to military activities as one component of the wider problem of heavy-metal pollution resulting from armed conflicts. The contamination of soil with zinc may originate from a range of military and conflict-related processes. These include the deposition of ammunition-derived materials and metal debris, corrosion and degradation of military vehicles and equipment, combustion of petroleum-based fuels and lubricants, and the demolition of industrial or storage infrastructure.

In the work devoted to soil contamination by mobile forms of heavy metals as a result of hostilities in the Mykolaiv region, it was found that compared to the control indicators of the 2009 agrochemical survey, the content of mobile zinc compounds in the studied agricultural plots increased by 11.4–111.4%. At the same time, the authors note that the MPC for mobile zinc compounds was not detected (Hryshchenko et al., 2025).

The observed increase in soil zinc concentrations following military activities corresponds with findings reported for the Sumy and Okhtyrka districts of the Sumy region. Their analysis demonstrated that zinc concentrations exceeded the respective background level in 90% of the examined samples. Moreover, the mean zinc concentration in the impacted soils was approximately 3.9-fold greater than the background value. Concentrations exceeding the maximum permissible level (MPC) for total zinc were identified in two soil samples collected from areas directly affected by military operations (Zaytsev et al., 2022).

Evidence from international research further supports the association between armed conflict and the accumulation of zinc and other potentially toxic elements in soils. A study conducted in Croatian territories exposed to different levels of military activity demonstrated that soils from areas subjected to intensive combat contained higher mean concentrations of Cu, Zn, Ni, Pb, P, and Ba than those collected from locations experiencing lower levels of military impact (Vidosavljević et al., 2013).

Research addressing the degradation and pollution of Ukrainian soils under the conditions of armed conflict demonstrates that military-related debris can substantially alter soil properties and functioning. In particular, the accumulation of metal fragments from damaged military equipment and ammunition, together with fuel-derived residues, contributes to a combination of mechanical disruption and chemical and physical degradation of the soil environment. Among the heavy metals investigated, Pb, Zn, and Cd exhibited the most pronounced contamination levels. These findings highlight the potential value of zinc as a marker of the intensity of anthropogenic pressure associated with military activities (Solokha et al., 2024).

Overall, the available scientific evidence indicates that zinc can serve as a responsive indicator of military-induced technogenic pressure on soil systems. Reliable evaluation of soil transformations following armed conflict requires comparison of current concentrations with pre-conflict or established background levels. In addition, assessment should extend beyond the total zinc concentration to include its mobile and potentially bioavailable fractions.

Method and Theory

The research, the results of which are presented in this article, was carried out within the framework of the research project "Study of the Agrochemical State and the Impact of Military Operations on Agricultural Lands to Ensure Sustainable Agro-production" in accordance with Agreement No. DZ/168-2025 dated February 12, 2025, concluded between the State Institution "Institute of Soil Protection of Ukraine" and the Ministry of Education and Science of Ukraine.

The object of research was 155 soil samples taken from 6 land plots with a total area of 691.2835 hectares, which were affected by hostilities in the territory of Romensky, Sumy and Okhtyrsky districts of Sumy region. For comparison, during agrochemical certification, the approximate area of

such plots is 8–20 hectares (Yatsuk et al., 2019). Samples were collected in accordance with the requirements of DSTU 4287:2004 (2005) using GPS navigation from a depth of 0–30 cm. The content of mobile forms of heavy metals (Zn) was determined using an ammonium acetate buffer (pH 4.8) according to DSTU 4770.2 in laboratory of State Institution "Institute of Soil Protection of Ukraine". Based on the cadastral numbers of the land plots provided by the land users, 6 experimental fields of agricultural enterprises were formed, the characteristics of which are presented in Table 1.

Table 1. *Research plots of agricultural purpose that have been affected by military actions in the territory in Sumy Oblast*

№ field	Area, ha	Location	Number of samples	Agricultural soil groups
Romny District				
1	130,3540	Ivanytsia village, Nedryhailiv Territorial Community	29	**53e***, 55e, 56e, 143, 165e and 209e
2	47,5221	Chemodanivka village, Nedryhailiv Territorial Community	11	**53e***
3	230,4127	Smile village, Khmeliv Territorial Community	52	53d, 55d, 121d, 141 and 165d
Sumy District				
4	266,7310	Verkhnia Syrovatka village, Verkhnosyrovatska Territorial Community	58	**53e***, 55e
Okhtyrka District				
5	13,3337	Hrebenykivka village, Boromlia Territorial Community	3	**53e***
6	2,93	Boromlia village, Boromlia Territorial Community	1	55e

* *High-value soils (State Committee of Ukraine, 2003)*

The assessment of the ecological and toxicological state was conducted according to the methodology of agrochemical certification (Yatsuk et al., 2019), taking into account maximum allowable concentrations. Statistical processing included the determination of average values, variation indicators, and the coefficient of variation.

Results

Zinc (Zn) is an essential micronutrient that plays a vital role in the functioning of plants. At the same time, its concentration in soils can reflect the intensity of anthropogenic pressure.

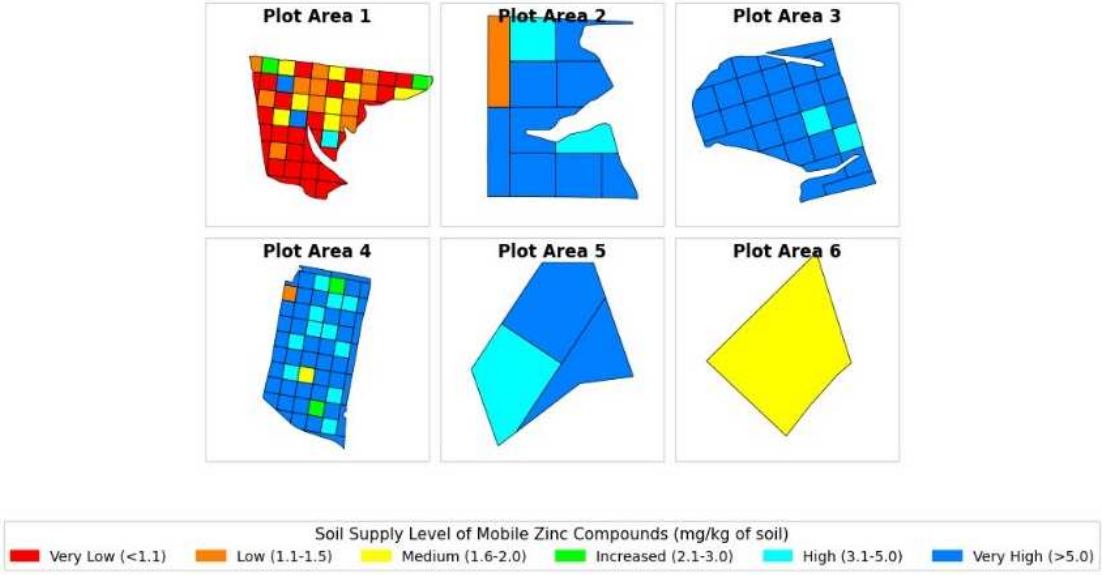

Figure 1. *Cartogram of Mobile Zinc Compound Content in Soil Distributed by 6 Plot Areas*

The weighted average content of mobile zinc compounds in the soils of the studied areas ranged from 1.36 to 19.64 mg·kg^{-1} (table 2).

Table 2. *Content of mobile zinc compounds in the post-war period in the territory in Sumy Oblast*

Plot No.	Content of mobile zinc compounds, mg·kg^{-1}	Level of availability / contamination	min…max, mg·kg^{-1}	V, %	Element content in the pre-war period, mg·kg^{-1}	Absolute increase, mg·kg^{-1}	Growth ratio compared to the pre-war level	Increase, %	Priority for further monitoring
1	19.64	elevated	3.65…74.62	87.1	0.33	+19.31	59.52	+5851.5	high
2	5.10	slight	1.27…11.7	60.7	0.26	+4.84	19.62	+1861.5	medium
3	1.36	low availability	1.23…7.89	84.6	0.29	+1.07	4.69	+369.0	low / medium
4	10.42	moderate	1.2…99.34	135.7	0.44	+9.98	26.68	+2268.2	medium / high
5	9.18	slight	3.76…15.68	67.3	0.23	+8.95	39.91	+3891.3	medium
6	1.93	medium availability	1.93	-	0.46	+1.47	4.20	+319.6	low / medium
Weighted average content	**8.74**				**0.40**				
Standard error	**2.33**				**0.04**				
Standard deviation	**6.81**				**0.10**				
Coefficient of variation	**78.0**				**27.0**				
Min	**1.36**				**0.23**				
Max	**19.64**				**0.46**				

Note: * *The contamination level is indicated in red, and the availability level is indicated in black*

An increased level of contamination was characterized by area number 1, where the content of mobile zinc compounds varied from 3.65 to 74.62 mg·kg^{-1}, while the coefficient of variation was 87.1%, which indicates a very high heterogeneity of indicators and may indicate the impact of hostilities. Maximum permissible concentrations (MPC) were exceeded in 8 soil samples from this field (23.80-74.62 mg·kg^{-1}). Compared with the pre-war period (0.33 mg·kg^{-1}), the weighted average indicator increased by 59.52%.

Moderate contamination was characterized by site number 4, where the content of mobile zinc compounds varied from 1.20 to 99.34 mg·kg^{-1} of soil, with a weighted average of 10.42 mg·kg^{-1}. Maximum permissible concentrations (MPC) were exceeded in 4 soil samples (27.34-99.34 mg·kg^{-1}). The coefficient of variation was 135.7%, which indicates an extremely high spatial heterogeneity of the indicator in the studied area. Compared with the pre-war period (0.44 mg·kg^{-1}), the weighted average indicator increased by 26.68 times.

Site number 2 (5.10 mg·kg^{-1}) and number 5 (9.18 mg·kg^{-1}) were characterized by a weak level of contamination. Within elementary plots, the variation was from 1.27 to 15.68 mg·kg^{-1} of soil. Compared with the pre-war period, the weighted average indicator increased by 19.62-39.91 times. Sites number 3 (1.36 mg·kg^{-1}) and number 6 (1.93 mg·kg^{-1}) were characterized by low and medium

levels of contamination. Compared to the pre-war period, the weighted average indicator increased by 4.20-4.69 times.

Conclusions

The conducted studies have shown that the content of mobile zinc compounds in agricultural soils of Sumy region is characterized by pronounced spatial heterogeneity, caused by anthropogenic factors, in particular the consequences of hostilities. The largest foci of contamination are located in areas number 1 and number 4. This confirms the local nature of the technogenic impact associated with hostilities. The indicated areas were subjected to mortar and artillery shelling, contained craters, and ammunition residues.

Conclusions

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